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# Control parameterisation for POD via software-in-the-loop simulation

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**Abstract:** The parameter optimisation of designed controllers for power systems is always a big concern and needs a lot of effort of researchers especially when the electricity grid becomes larger and more complex. This study proposes a control parameterisation using genetic algorithms (GAs) for power oscillation damping (POD) incorporating synchronous condensers (SCs) via software-in-the-loop simulation to enhance the damping and frequency stability for low-inertia systems. A closed-loop interfaced setup among real-time digital simulator, MATLAB, and OLE for process communication running in real time is analysed and implemented to optimise the POD parameters of a SC. Furthermore, a Prony technique based on the system measurement is applied to find out the frequency and damping ratio of the dominant oscillation mode. The POD optimal parameters are determined by the GA objective function that maximises the damping ratio of the dominant oscillation mode. The effectiveness of the proposed method in damping power oscillations and frequency stability improvement is verified through simulation results of the future western Danish power system. Simulation results demonstrate that the proposed approach offers good performance for parameter optimisation of the POD.

## 1 Introduction

The rapid increase of converter-based generation in the grid makes system dynamic characteristics significantly changing. Instability issues resulted from low-frequency oscillations because of low-inertia operating conditions and weak interconnections among power systems are, therefore, more significant. This requires innovative solutions for an optimisation of power system elements and controllers to guarantee secure operation.

Traditionally, many supplementary controllers are implemented in power systems to address oscillatory stability issues. Power system stabilisers (PSSs) implementation to existing power plants is used as an auxiliary excitation control to damp oscillations for power system stability enhancement. Besides, power oscillation damping (POD) using flexible AC transmission systems (FACTS) devices that control the angle of injection buses to adjust the power transferring on transmission lines [1, 2]. Coordinating existing PSSs with supplementary control of other components such as wind power plants [3, 4] or FACTS devices [5–7] are examined as well. However, how to optimise the control parameters is always a concern for control engineers. Several researchers have implemented optimisation algorithms for determining optimal parameter set of controllers. In [8], a genetic algorithms (GAs) optimisation is applied for tuning control parameters of the proportional–integral controller subject to the  $H_\infty$  constraints in terms of linear matrix inequalities of the state-space system model of the three-area power system. Safari *et al.* [9] propose a tuning strategy for robust pulse-width modulated series compensator damping controller based on an augmented Lagrangian particle swarm optimisation which satisfies the multiple  $H_\infty$  performance criteria for FACTS controller. A PSS parameter optimisation using a trajectory sensitivity approach is examined in [10] for a multi-machine power system. A gradient-based non-linear parameter optimisation of FACTS devices via real-time digital simulator (RTDS) is investigated in [11]; however, there is a limit for the optimisation algorithm implementation in RTDS.

With the dominance of renewable generators in the modern power systems, new stability issues and requirements for the controls are introduced for the renewable-based systems. To have a smooth transition to the renewable energy system, a POD control design adapting to the modern system characteristics is extremely

necessary. Synchronous condenser (SC) is proposed as a potential solution for low-inertia systems to support inertia and short-circuit power [12–14].

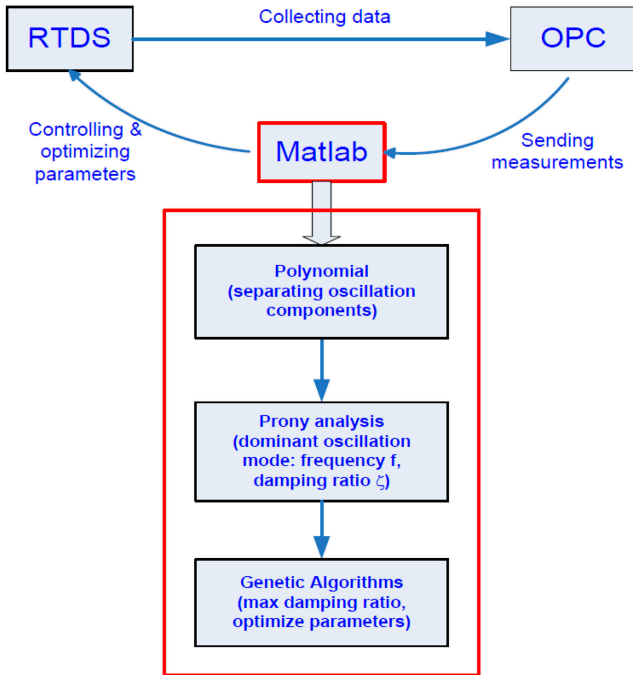
To address these issues, this paper presents a software-in-the-loop simulation for parameter optimisation of POD incorporating in SCs which uses a non-linear optimisation tool to enhance the power oscillation and frequency stability of low-inertia systems.

The rest of this paper is organised as follows. The software-in-the-loop simulation for parameter optimisation of POD which is a closed loop and runs in real time with RTDS, object linking and embedding (OLE) for process communication (OPC), and MATLAB communications is introduced in Section 2. Section 3 presents the methodology using for parameter optimisation for POD. A test result based on the future western Danish power system is investigated in Section 4 to verify the benefit of software-in-the-loop (SiL) simulation of the POD parameter optimisation. Some important conclusions are finally drawn in Section 5.

## 2 Software-in-the-loop setup

The perspective future western Danish power system run in RTDS platform is driven by a MATLAB script for system start-up and disturbance simulations. The data of the system is collected by the OPC server and sent directly to MATLAB workspace. In MATLAB, the signal is processed first to remove the fundamental frequency component from the response signal. The oscillation component is analysed by Prony analysis for determining the frequency and damping ratio of the dominant oscillation mode. The damping ratio is maximised by GA objective function to find the better parameters of POD and update the RTDS model for further verification. These steps are iterative by a closed loop and run in real time with RTDS, OPC, and MATLAB communications as shown in Figs. 1 and 2. The loop will continue until the objective function satisfying the damping ratio maximisation of the dominant mode constraint to determine the optimal values of POD parameters.

To communicate with MATLAB, RTDS has to run the ‘ListenOnPort’ command and becomes a transmission control protocol (TCP) server. This server listens to a designed port and waits for an incoming connection request from MATLAB script. Once the connection is established, RTDS runtime becomes a



**Fig. 1** System arrangement of SiL simulation

socket server and MATLAB is a socket client. RTDS runtime is controlled by a MATLAB script via the TCP communication. To collect the data from OPC, a communication setup is established between MatrikonOPC and MATLAB through OPC toolbox that allows accessing to live and historical OPC data directly from MATLAB/Simulink.

### 2.1 RTDS setup

The whole DK1 system is modelled and compiled in RSCAD/Draft. To run the system by a MATLAB script, a communication connection is established between RSCAD/runtime and MATLAB. Once the connection is implemented, RTDS runtime becomes a socket server and MATLAB is a socket client. RSCAD/runtime is commanded and run in real time by a MATLAB script via the TCP server [15]. In addition, the new parameter set of POD controller is updated via this communication as well.

RTDS exchanges data to external equipment over a local area network/wireless area network using the distributed network protocol (DNP). To send the measurement data to OPC, a gigatransceiver network communication card (GTNET) card equipped with the DNP firmware is installed in one of the RTDS racks, where the measured signal must be located in. A point mapping text file with a '.txt' suffix is used to map DNP data points to input/output signal names assigned in RSCAD/draft.

### 2.2 OPC setup

To collect the data from RTDS, a communication channel between RTDS with MatrikonOPC is setup with three steps including RTDS network channel, RTDS network host, and RTDS DNP3, which is described in detail in [16]. After the communication is established, RTDS and OPC can exchange the data to each other. The measurement data is collected in the OPC server and sent to MATLAB for next steps.

### 2.3 MATLAB programme

A MATLAB script commands and runs the system in real time at RSCAD/Runtime through TCP communication. To acquire the data at the OPC server, a connection is a setup in a MATLAB script to create a group object with specifically defined properties. After getting the data and then through a signal processing to convert to the proper format, it is retrieved in MATLAB workplace for further analysis. When the data is sent to MATLAB, OPC cleans up and disconnects to prepare for the next data collections. A polynomial

function is implemented to remove the fundamental frequency component from the response signal. After that, the Prony technique is applied to extract the frequency and damping ratio of the dominant oscillation mode. On the basis of the damping ratio, the better parameter set of POD controller is found out based on GA objective to achieve the damping ratio maximisation of the dominant oscillation mode.

The parameter set is sent to RSCAD/Runtime by a MATLAB command for the next iteration. These steps are repeated continuously until one of the termination parameters is achieved. The GA may be terminated after a certain number of generations when the objective value does not enhance after a certain generation. As a result, a near-optimal or optimal solution for POD parameter set is determined. The entire procedure is illustrated in Fig. 2.

## 3 Methodology

In this section, Prony analysis is first explained how to extract the information of measurement data. After that, the application of GA for POD parameter optimisation is described.

### 3.1 Prony analysis

Prony analysis is a least-square approximation technique of fitting a linear sum of exponential terms to a measured signal. A brief overview of this technique is given in [17]. The important feature of this technique is directly determining the frequency, damping ratio, energy, and relative phase of modal components present in a given measurement signal by an extending Fourier analysis [18]. The ability to extract such information from transient signal simulations would overcome the computing burden of the linear model for large-scale systems.

Consider a generally continuous signal  $y(n)$  that is to be modelled by

$$y(n) = \sum_{i=1}^p (b_i z_i^n) = \sum_{i=1}^p A_i e^{j\theta_i} e^{(\alpha_i + j2\pi f_i)n\Delta t} \quad (1)$$

$$\text{with } \begin{cases} b_i = A_i e^{j\theta_i} \\ z_i = e^{(\alpha_i + j2\pi f_i)n\Delta t} \end{cases}$$

where  $n = 0, 1, 2, \dots, N-1$  with  $N$  is the sampling number;  $\Delta t$  represents the time interval of sampling;  $p$  is the order of Prony mode;  $A_i$  and  $\theta_i$  are the amplitude and inception phase angles of the  $i$ th oscillation mode; and  $f_i$  and  $\alpha_i$  represent the frequency and damping ratios of the  $i$ th oscillation mode, respectively.

Overall, the Prony analysis can be summarised into three steps:

- (i) Constructing a linear prediction model from the measured data and solving it.
- (ii) Computing the discrete-time poles of the characteristic polynomial equation generated by the linear model which in turn results in the eigenvalues.
- (iii) From these eigenvalues, the damping ratios and oscillation frequencies and related parameters could be extracted.

Before determining the information of the measured data, a signal processing step is implemented to remove the fundamental frequency. This step separates the oscillatory component for Prony analysis conduction. The Prony analysis obtains many oscillation modes which include dominant modes and disturbance modes. This results from the mixing noise and trend in the measurement which cannot be eliminated completely in the signal processing step.

The dominant mode is recognised by the energy analysis approach which evaluates the contribution of each oscillation mode, is expressed as follows:

$$E_i = \sum_{n=0}^{N-1} (R_i Z_i^n)^2 \quad (2)$$

where  $E_i$ ,  $R_i$ , and  $z_i$  are the energy, the amplitude, and the pole of the  $i$ th oscillation mode, respectively;  $i = 1, 2, \dots, p$ .

The dominant mode is the biggest energy contribution to the oscillation. A comparison of Prony approximate and measurement is shown in Fig. 3 which presents how accurately the Prony analysis works in this paper.

### 3.2 Genetic algorithms

GA is a global heuristics parameter search technique based on genetic operators to find optimal or near-optimal solutions for each specific problem [19, 20]. Unlike the traditional optimisation approaches that require one starting point, GA uses a set of points (chromosomes) as the initial condition and each chromosome is evaluated for its performance according to the objective function which characterises the problem to be solved and defined by the designers. A group of chromosomes is called a population. In this paper, five parameters of the POD controller are optimised by a

damping ratio maximisation objective function of GA. The process of GA is applied as follows:

(i) *Initialisation*: A number of individuals which represent the POD parameters are randomly created according to the initial population, upper and lower bound settings.

(ii) *Objective evaluation*: Using a selection operator, the algorithms select the best result for each individual in accordance with their values defined by the objective function. The main goal of the control system is the damping ratio maximisation of the system oscillation mode, i.e.

$$f(x) = \max \left( \xi = -\frac{\alpha}{\sqrt{\alpha^2 + \beta^2}} \right) \quad (3)$$

where  $\alpha$  and  $\beta$  are real and imaginary parts of the dominant mode, respectively. It means that GA finds out the variables  $x$  based on boundary settings to maximise the damping ratio  $\xi_i$  of the oscillation mode.

(iii) *Reproduction*: A new set of chromosomes are generated from the selected parameters in step 2 using selection, crossover, and mutation operators. These genetic operators ensure a larger average objective value for the next generation.

(iv) *Termination flagged*: These three steps are repeated continuously until one of the termination parameters is achieved. The GA may be terminated after a certain number of generations when the objective value does not enhance after a certain generation.

### 4 Case study

To verify the performance of SiL simulation of POD parameter optimisation, a load increase scenario is investigated in this section.

Fig. 4 shows comparative results of system frequency, rate of change of frequency (ROCOF), active power on transmission line KAS to LAG, high-voltage DC (HVDC) link from DK1 to DK2, and SC responses without in the dotted red line and with GA-based POD in the solid blue one. From the comparative results, while uncontrolled system exhibits a severe oscillation and large frequency deviation, the system with the POD controller performs a better damping and frequency deviation improvement. As seen that the system frequency in Fig. 4a, without POD it experiences a large and long oscillation (the dominant mode with 0.596% damping ratio) as well as a huge deviation (0.3 Hz) before getting a new equilibrium. On the contrary, with GA-based POD these parameters are significantly improved 14% of damping ratio and 0.18 Hz of the frequency deviation. By comparing ROCOF, a faster damping and a quicker settling down are obviously seen in Fig. 4b with POD controller.

An opposite trend is observed from the reactive power response of SC during the disturbance without and with POD controller. Instead of rapidly increasing the reactive power from around 31 Mvar to ~114 Mvar to keep the voltage constant at the nominal

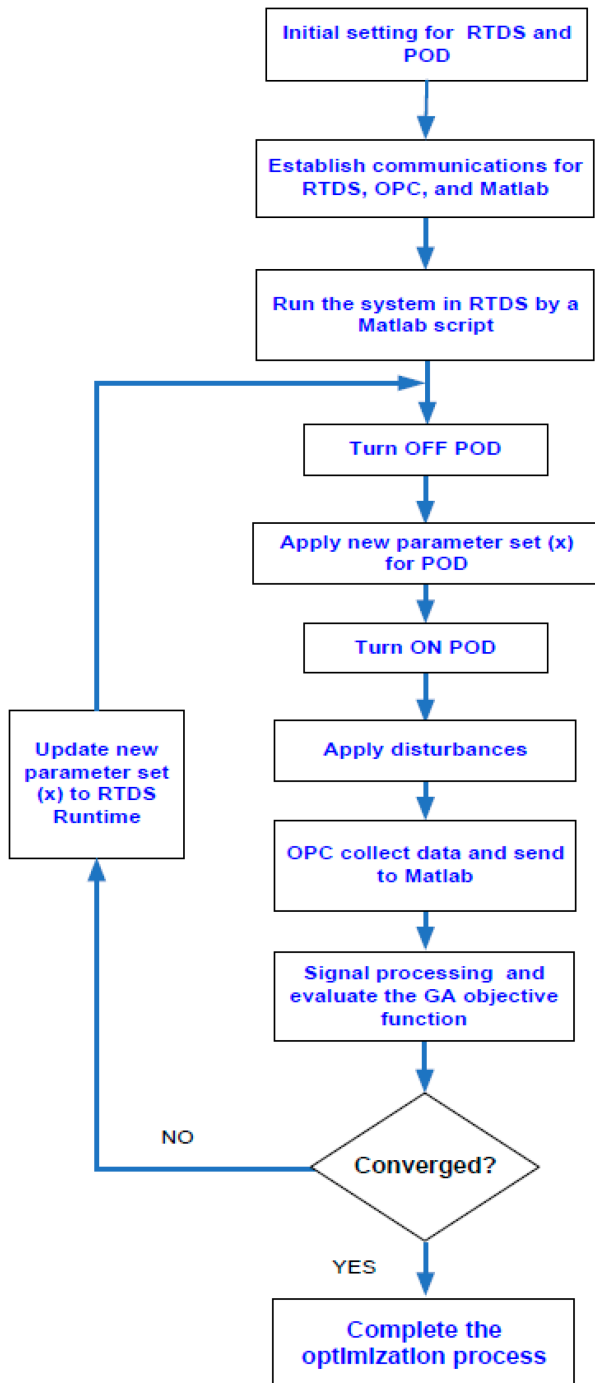


Fig. 2 Overall procedure of optimisation process with SiL

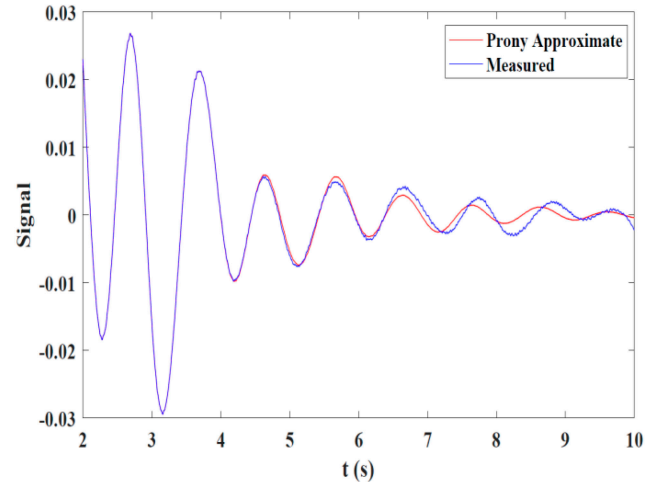
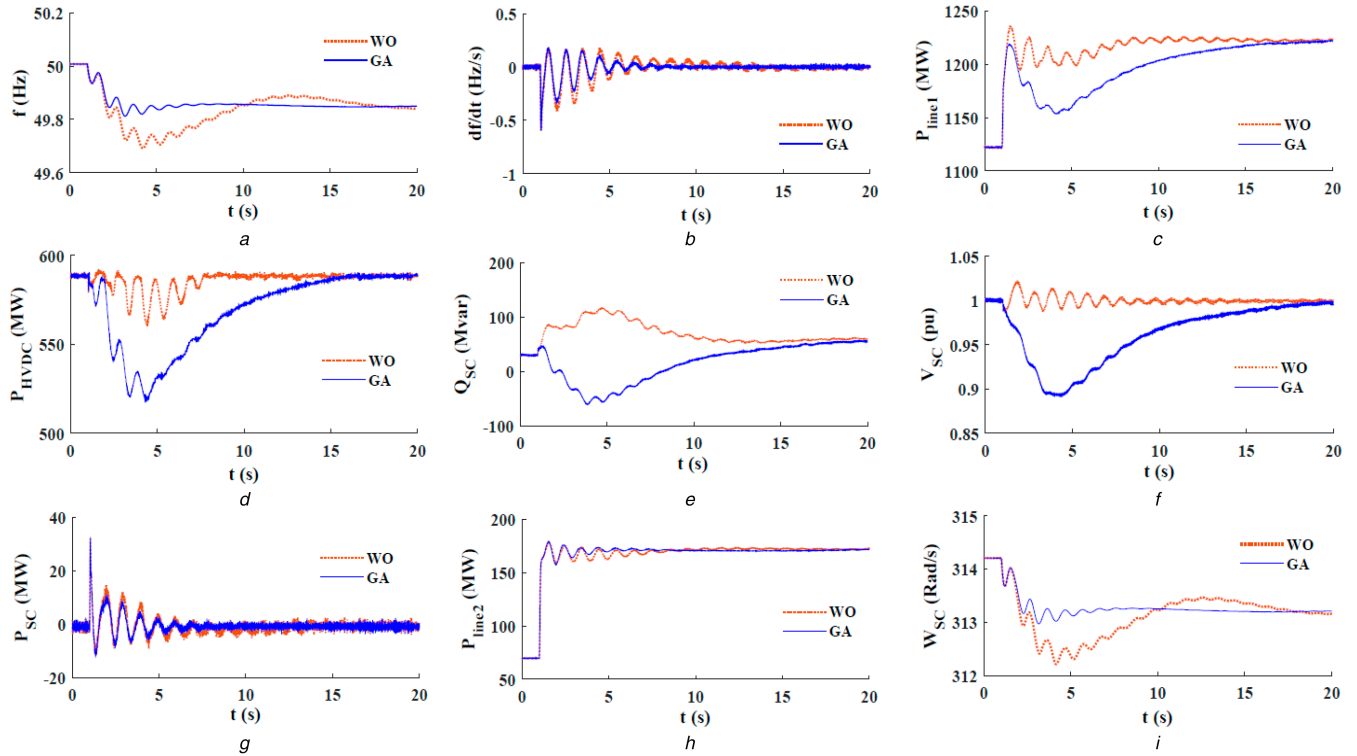


Fig. 3 Comparison of Prony analysis and the measurement signal





**Fig. 4** Load increase scenario

(a) System frequency, (b) ROCOF, (c) Active power from KAS to LAG, (d) Active power from DK1 to DK2 through HVDC connection, (e) Reactive power of SC, (f) Terminal voltage of SC, (g) Active power of SC, (h) Active power from LAG to MAL, (i) Rotor speed of SC

**Table 1** Without and with GA comparison of dominant mode

Cases	Dominant mode	Frequency, Hz	Damping ratio	Frequency peak, Hz
without	$-0.037 + j6.217$	0.992	0.00596	49.7
genetic algorithm (GA)	$-0.998 + j6.8452$	1.09	0.145	49.82

value as WO case, POD decreases the terminal voltage by absorbing around 90 Mvar reactive power (from 31 Mvar to around -59 Mvar) to control the power flow. Consequently, a large decrease and less oscillation are observed from the active powers on the transmission lines and HVDC link with POD controller as shown in Fig. 4.

As expected, the active power of SC rapidly supports kinetic energy and quickly settles down while the rotor speed has significantly improved both the deviation and the damping with the POD controller as seen in Figs. 4g and i. As a result, the power oscillation and frequency stability are significantly improved during the disturbance with the POD controller. The parameters shown in Table 1 summarise the Prony analysis of the dominant mode with a significant enhancement of the system with the POD controller.

## 5 Conclusion

To deal with the oscillatory stability issue for the modern power system, where new stability issues and requirements for the controls are introduced, this paper proposes an SiL simulation for parameter optimisation based on a non-linear optimisation tool of POD controller to enhance the stability issue of low-inertia systems. Furthermore, a Prony technique is applied to extract the system oscillation characteristic from the data measurement, which benefits for large-scale systems with thousands of variables. It can be seen clearly from the comparative results that SiL simulation can offer a good parameter set for POD to enhance the damping and frequency stability during the disturbances. In addition, parameter optimisation algorithm can help control designers saving time while still offers a near-optimal or optimal solution for the control parameter set. This SiL simulation can be applied to any optimisation tool by modifying the algorithm in MATLAB command.

## 6 Acknowledgments

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